Intelligent tuned PID controller for wind energy conversion system with permanent magnet synchronous generator and AC-DC-AC converters

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ABSTRACT

This paper presents the intelligent tuned PID controller-based Single Ended Primary Inductor Converter (SEPIC) for Maximum Power Point Tracking (MPPT) operation of Wind Energy Conversion System (WECS). As the voltage and frequency of the Permanent Magnet Synchronous Generator (PMSG) varies with the wind speed changes, Intelligent controlled SEPIC is utilized to maintain the constant DC link voltage. The intelligent tuned PID controller combines the advantages of both conventional and soft controllers. The 1.5MW variable speed WECS (VSWECS) with AC-DC-AC converter is developed using MATLAB/Simulink software. PMSG delivers a load/utility grid through an uncontrolled diode rectifier, intelligent controlled SEPIC and three phase inverter. The real time implementation of the proposed system is done by the DSP processor MSP430F5529. The performance of the SEPIC is tested in both simulation and experiment at different wind speed conditions. The performance of the proposed Intelligent MPPT control of SEPIC are compared with the conventional PID controller. Intelligent tuning of PID controller such as Fuzzy-PID, and ANFIS-PID is implemented in the proposed system and results are compared. The simulation and experimental results reveals that the proposed ANFIS method provide improved performance than the conventional PID method in terms of power quality.

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1. INTRODUCTION

The electrical energy demand increases day by day because of the increase in population around the world and shortage of the natural sources like coal, oil and natural gas for the generation of electricity.The renewable energy sources such as solar energy, wind energy, hydroelectric, biomass, and geo thermal solve the problem caused by the natural resources. The advantages of renewable power generations are sustainable, clean energy, non-pollutant, less maintenance, less cost, no carbon dioxide emission, or other chemical pollutant. However, the renewable energy sources mainly depend on unpredictable weather condition and geographical conditions for the production of good quality of electrical power. Out of all the renewable energy sources, the most promising source satisfying all the requirements is the wind. Wind energy is one of the most available and exploitable form of renewable energy. The worldwide wind

energy capacity has stepped forward and it is an important competitor to the conventional energy sources. In another five years wind energy generation is predictable to rise to 1.26 million of MW, which will cover 12% of worldwide energy capacity [1].

Presently, the Variable Speed Wind Energy Conversion System (VSWECS) is equipped with direct drive Permanent Magnet Synchronous Generator (PMSG). Variable speed wind turbine [2] is most popular due to the advantages like simple structure, improved energy capture, maximum power extraction, low losses, good power factor, good power quality, and more efficiency. PMSG machines are more efficient than other machines because of their advantages such as less weight, small size, and flexible design structure [3].

Electrical energy generated by the VSWECS with PMSG is of variable amplitude and variable frequency in nature. The power electronic controller plays an important role for the power quality enhancement [4]. The variable AC voltage is converted into variable DC by AC-DC rectifier stage [5]. The unregulated DC input supply is given to DC-DC SEPIC, which should be regulated for the standalone system or grid connected system. To achieve this, a negative closed loop control is incorporated in the DC-DC converter, which automatically adjusts the duty cycle in case of input supply variation. PID controller has been used to compensate for change in error resulting from the difference between the feedback voltage and reference voltage. A Maximum Power Point Tracking (MPPT) step and search point algorithm is developed to track maximum power from the variable speed wind turbine by generating a suitable reference voltage to the controller [6].

PID controllers play an important role in the control of the duty cycle of power electronic switches of AC-DC-AC converters due to its robust nature, simple structure, and easy implementation. However due to the simple structure, PID controllers are suited for first and second order system only. For higher order and nonlinear systems, tuning of PID [7] [8] parameters such as proportional gain K_p, integral gain K_i and derivative gain K_d is a crucial issue. One of the classical method of tuning is Ziegler-Nichols (ZN) [9] technique based on some controller assumptions and it needs further tuning. The downside of this method is the excessive overshoot and oscillatory response. Cohen-Coon [10] developed a method with the PID controller parameters derived based on load disturbance rejection. Even though a better method, the results are not much better than ZN technique. The Cohen-Coon method is applicable only for first order models. The other tuning methods are relay auto tuning method [11], Internal Mode Control (IMC) based method proposed by Morari [12], tuning method based on optimization proposed by Astrom and pole placement method. However all the methods are suitable for lower order and linear system. The methods are not suitable for nonlinear system.

This paper focuses on analyzing intelligent method of tuning PID controller for DC-DC converter applications. The time domain analysis of the proposed system was carried out in MATLAB/SIMULINK. The intelligent technique provides better performance in terms of rise time, settling time, and overshoot than the conventional tuning methods. This paper is organized as follows. Section 2 deals with the modeling of wind energy conversion system. Designing of SEPIC is described in section 3. The methods of tuning PID controller is explained in section 4. It is followed by MPPT algorithm used for reference voltage generation. Section 5 deals with the simulation and experimental results. Section 6 summaries the conclusion and future scope.

2. WECS WITH AC-DC-AC CONVERTER

The proposed wind energy conversion system consists of constant pitch angle wind turbine, Permanent magnet synchronous generator, a uncontrolled diode rectifier, a voltage controlled Single Ended Primary Inductor Converter (SEPIC) and three-phase inverter. It is shown in Figure 1.

2.1. Modeling of mechanical system

The non-uniform heating of sun on the earth's surface causes the circulation of air in the atmosphere. The energy depends on the air density ρ (kg/m^3), swept area A(m^2) and wind speed v (m/sec). The power extracted by the wind turbine in uniform wind field is given by the rate of change of energy and expressed as in (1):

$$P_m = \frac{1}{2}\rho A v^3 C_p\left(\lambda,\beta\right) \tag{1}$$

where;
$C_p(\lambda,\beta)$is known as power coefficient
λ is the tip speed ratio.

The general expression for the power coefficient is expressed by (2):

$$C_p(\lambda,\beta)=C_1\left(\frac{C_2}{\lambda_i}-C_3\beta-C_4\right)^{\frac{-C_5}{\lambda_i}}+C_6\lambda \tag{2}$$

The coefficients C_1 to C_6 are C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21 and C_6=0.0068. The maximum value of Cp(λ, β) is 0.593 for conventional wind turbine. The ratio of the speed of the rotor blade tip to the speed of the wind is the tip speed ratio (TSR). Every rotor has an optimum tip speed ratio at which its maximum efficiency is achieved and which characterizes the rotor. The tip speed ratio is given by (3):

$$\lambda=\frac{R\omega_t}{v}=\frac{2\pi Rn}{v} \tag{3}$$

where ω_t is the turbine speed or rotor speed in rad/sec (4).

$$\frac{1}{\lambda_i}=\left[\frac{1}{\lambda+0.089}-\frac{0.035}{\beta^2+1}\right] \tag{4}$$

Blade pitch angle is decided by shape of the turbine blade. TSR is a controllable parameter and affected by the turbine speed. The optimum or maximum value of power coefficient Cp is achieved at β = 0.

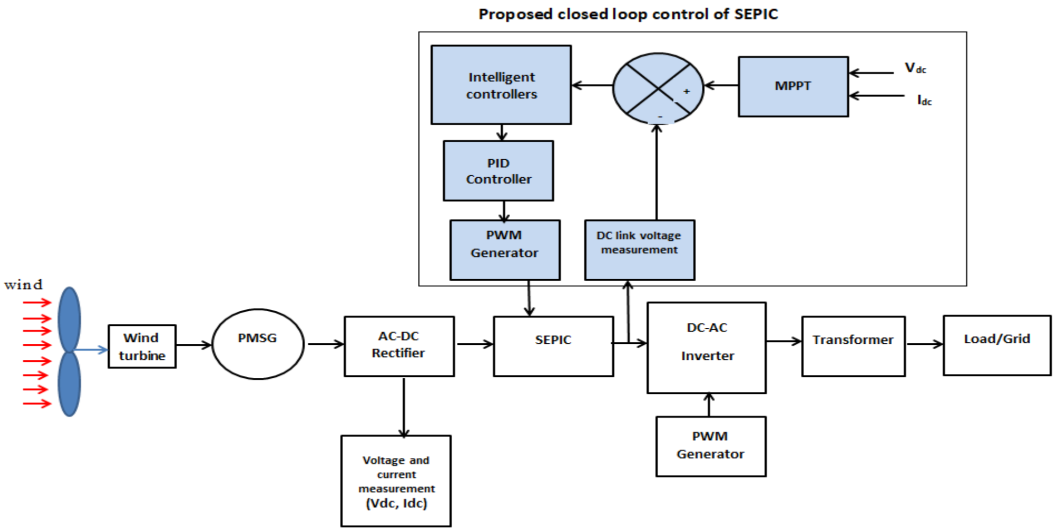

Figure 1. Proposed model for the variable speed wind energy conversion system

2.2. Modeling of electrical system

Generators are used to convert mechanical energy from turbine into electrical energy, which is fed into the electrical grid. The dynamic equations give the mathematical model of the PMSG as below (5-6):

$$\frac{di_{sd}}{dt}=\frac{1}{L_d}u_{sd}-\frac{R_s}{L_d}i_{sd}+\frac{L_q}{L_d}p\omega_r i_{sq} \tag{5}$$

$$\frac{di_{sq}}{dt}=\frac{1}{L_q}u_{sq}-\frac{R_s}{L_q}i_{sq}+\frac{L_d}{L_q}p\omega_r i_{sd}-\frac{\lambda_m p\omega_r}{L_q} \tag{6}$$

where

i_{sd}, i_{sq} are the d and q axis stator current.

L_d, L_q are the d and q axis stator inductance.

R_s is the stator resistance.

λ_m is the permanent magnet rotor flux

p is the number of pole pairs.

The electromagnetic torque equation can be given by (7):

$$T_e = \frac{3}{2} p \left[\lambda_m i_{sq} + \left(L_d - L_q \right) i_{sq} i_{sd} \right] \tag{7}$$

3. DESIGN OF SEPIC DC-DC CONVERTER

The Single Ended Primary Inductor Converter (SEPIC) is a type of non-isolated converter and is extensively used in medium to high voltage power conversion [13]. The output voltage is greater than or less than the range of input voltage. Figure 2 shows the basic topology of SEPIC.

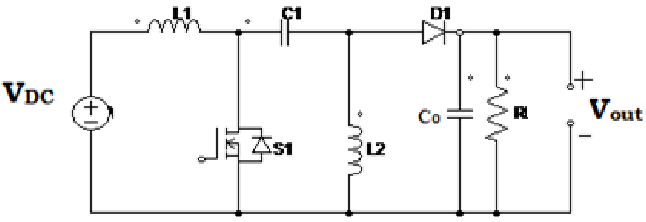

Figure 2. Basic topology of SEPIC

When switch S is turned on, capacitor C_1 is charged to input voltage V_{in}, and hence the voltage across L_2 is $-V_{in}$. While Switch is on, magnetic energy is stored in inductor L_1 from input voltage and energy is L_2 is stored from C_1 When switch S_1 is turned off, the voltage across inductor L_2 will be Vo. While Switch is off, the current flowing through L_1 also flows through C_1 and D_1 then into C_0 on the load. The relation between input current, output current, input voltage, output voltage and duty cycle are expressed below (8-9):

$$\frac{V_{out}}{V_{DC}} = \frac{D}{1-D} \tag{8}$$

$$\frac{I_{DC}}{I_{out}} = \frac{D}{1-D} \tag{9}$$

The value of the inductor is selected based on the following (10):

$$L_1 = L_2 = L = \frac{V_{in(\min)} * D_{\max}}{\Delta I_i * f_{sw}} \tag{10}$$

where ΔIi is the peak-to-peak value of ripple current at the minimum input voltage and fsw is the switching frequency.

The value of coupling capacitor C_1 depends on the RMS current, which is given by (11):

$$I_{cs(rms)} = I_{out} * \sqrt{\frac{V_{out} + V_D}{V_{DC(\min)}}} \tag{11}$$

The coupling capacitor is selected for large value of $I_{cs(rms)}$ when referred to the output power of SEPIC. The voltage of the capacitor must be greater than the maximum input voltage (12).

$$\Delta V_{c1} = \frac{I_{out} * D_{\max}}{C_1 * f_{sw}} \tag{12}$$

The output capacitor is selected to handle the large value of ripple current.

4. MAXIMUM POWER POINT TRACKING ALGORITHM

Variable Speed Wind Energy Conversion System (VSWECS) integrated with power electronic converters are becoming most popular nowadays because of maximum power point tracking (MPPT) algorithm. For an uncontrolled three-phase diode rectifier the output voltage V_{dc} is directly proportional to the phase voltage generated by the PMSG [14]. Hence the generated power /phase is given by (13):

$$P_{gen} = \frac{\Omega_r k I_f}{R_a}\left(V_{dc} - k I_f \Omega_e\right) \tag{13}$$

where:
Ω_e is the electrical angular speed.
I_f is the filed current.
V_{dc} is the diode rectifier output voltage.
Ω_r is the angular velocity of the rotor.
R_a is the armature current.

V_{dc} is a function of field current and electrical angular speed. Extracted power from the wind can be controlled by varying Vdc.

From the characteristics of wind turbine (14-15)

$$\frac{dP_{mech}}{d\Omega_r} = 0 \tag{14}$$

$$\frac{dP_{mech}}{d\Omega_r} = \frac{dP_{mech}}{dV_{dc}} \cdot \frac{dV_{dc}}{d\Omega_e} \cdot \frac{d\Omega_e}{d\Omega_r} = 0 \tag{15}$$

Then (16)

$$\frac{dP_{mech}}{dV_{dc}} = 0 \tag{16}$$

From (16), it is clear that the maximum power extraction [15] depends on V_{dc} in a single point. The maximum power can be tracked by searching rectifier power, instead of wind speed and a direction.

First, initiate the step and search point algorithm. Set the reference DC voltage V_{ref}. Then measure the Diode rectifier output voltage and current, calculate the DC output power $P_{dc}=I_{dc}\ V_{dc}$. Next increase or decrease the V_{ref} voltage according to flow chart shown in Figure 3.
The new reference DC voltage is given by the following (17):

$$V_{ref}(n) = V_{ref}(n-1) \pm \Delta V_{dc} \tag{17}$$

Then the new DC power is calculated as (18):

$$P(n) = I_{dc}(n).V_{dc}(n) \tag{18}$$

Compare P (n) with P (n-1). Depending upon the wind speed conditions the following conditions should be met.

The process will continue until the maximum power is reached. For the cut in speed to rated speed, MPPT extracts maximum power from the turbine. The SEPIC is used to regulate the DC voltage across the capacitor C_0. In the proposed model, MPPT controller is used to deliver the reference DC voltage, which is compared with the actual DC output voltage from the SEPIC.

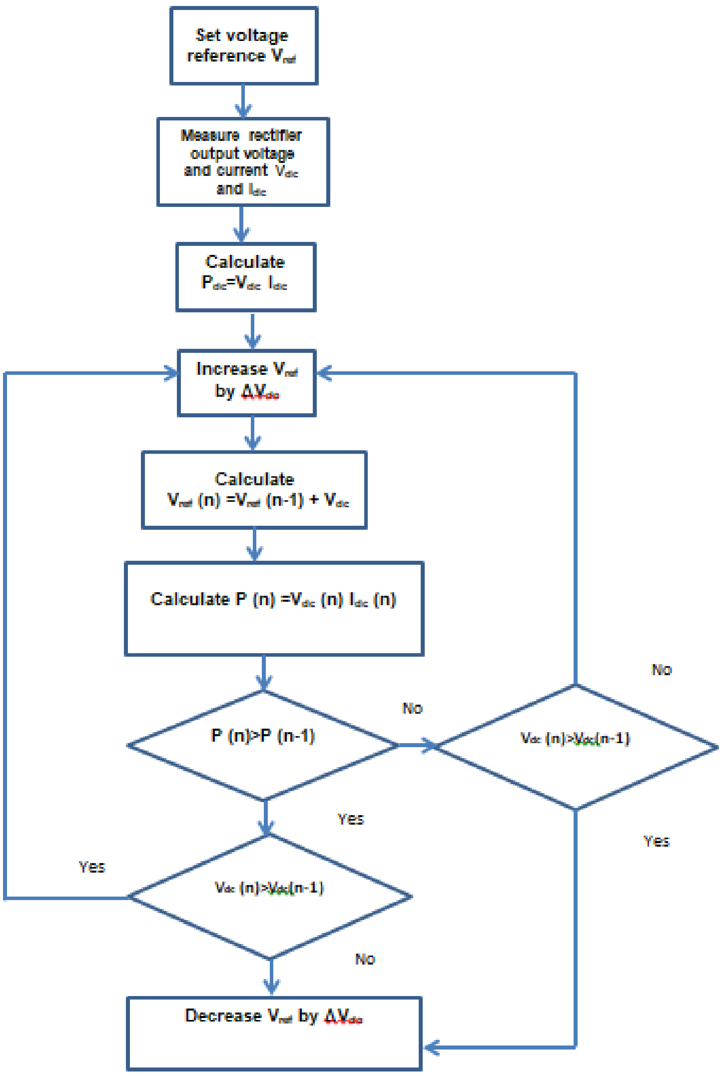

Figure 3. MPPT algorithm

5. METHODS OF TUNING PID CONTROLLER

A PID controller is a closed loop feedback system mainly used in industrial control systems. It continuously calculates the value of error as the difference between the reference value and measured variable and applies a correction depends on the PID parameters of K_p, K_i and K_d. The process of obtaining the PID controller parameters in order to get desired output from the system called tuning.

5.1. Standard PID controller

The mathematical representation of control signal provided by PID controller is given by (19-20):

$$u(t) = K_p\left[e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right] \tag{19}$$

but $K_i = \frac{K_p}{T_i}$, $K_d = K_p T_d$

then (17) becomes

$$u(t) = K_p e(t) + K_i\int e(t)dt + K_d\frac{de(t)}{dt} \tag{20}$$

where

T_i is the integral time constant.

T_d is the derivative time constant.

Figure 4 shows the block diagram of conventional PID controller.

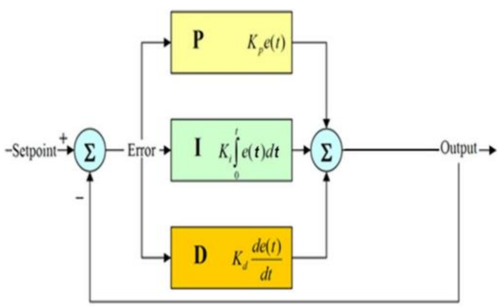

Figure 4. Block diagram of conventional PID controller

5.2. Fuzzy logic based PID (Fuzzy-PID)

It is difficult to meet the desired control performance by using Conventional PID controller with time delays, unknown non-linarites, and change in system parameters. Hence, in order to achieve required performance, automatic tuning of PID parameters is needed. The automatic tuning has been done by using fuzzy logic control. The block diagram of a fuzzy PID controller shown in Figure 5. Figure 6 shows the block diagram of the fuzzy logic controller.

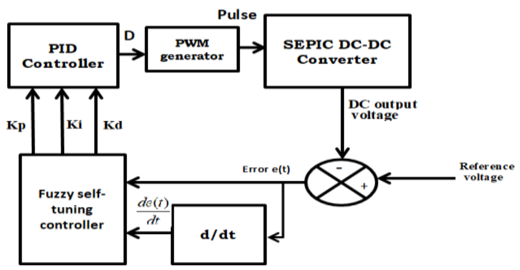

Figure 5. Block diagram of Fuzzy-PID controller

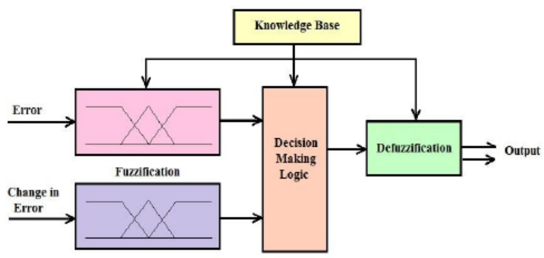

Figure 6. Block diagram of fuzzy logic controller

Fuzzy logic controller contains fuzzification system, rule base fuzzy inference system and defuzzification system. Fuzzification is the process of converting the input values into fuzzy values. Then fuzzy values are processed by fuzzy inference system as per the rule base. In the defuzzification process, fuzzy values are converted back into exact values [16, 17].

The input to the fuzzy logic controller are the error e(t) and derivative of error Δe(t). The output from the controller are proportional gain K_p, integral gain K_i and derivative gain K_d. The input variables and output variables have seven membership functions. The membership functions are Z (zero), SP (Small Positive), SN (Small Negative), MP (Medium Positive), MN (Medium Negative), VP (Very Positive), VN (Very Negative). The membership functions of error e(t) and derivative of error Δe(t) are shown in Figure 7 and Figure 8. The membership function for output Kp, Ki, and Kd is shown in Figure 9. The rule base for the fuzzy PID shown in Table 1.

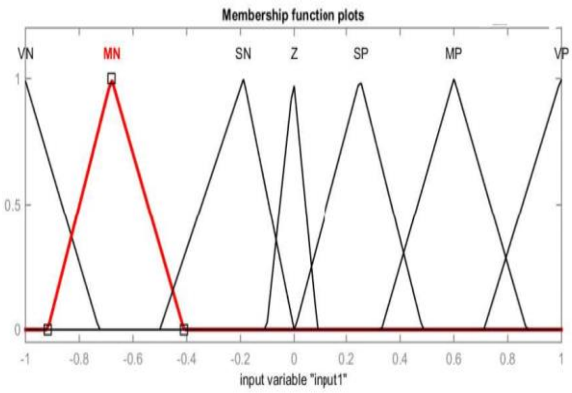

Figure 7. Membership function for error e (t)

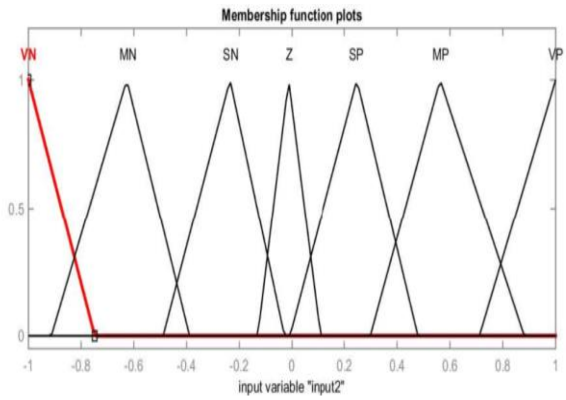

Figure 8. Membership function for error Δe (t)

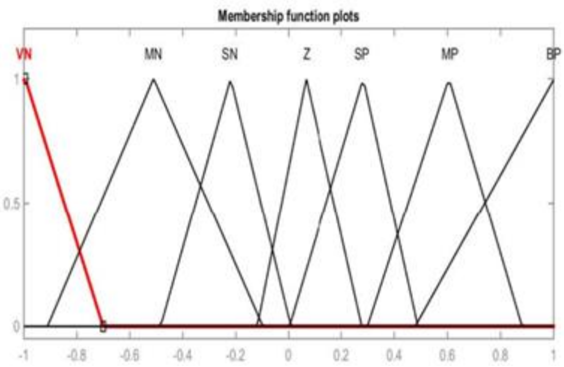

Figure 9. Membership function for outputs K_p, $K_{i,}$ and K_d

Table 1. Rule base for fuzzy PID

Error	Derivative of error Δe (t)					
e(t)	VN	MN	SN	Z	SP	MP	VP
VN	VP	VP	MP	SP	SP	Z	SN
MN	MP	MP	MP	SP	SP	Z	SN
SN	MP	MP	MP	SP	Z	SN	SN
Z	MP	MP	SP	Z	SN	MN	MN
SP	SP	SP	Z	SN	SN	MN	MN
MP	SP	Z	SN	MN	MN	MN	BP
VP	Z	SN	MN	MN	MN	VN	VN

5.3. ANFIS based PID (ANFIS-PID)

Adaptive Neuro Fuzzy Inference system is a special type controller, which combines an artificial neural network and fuzzy logic controller. Figure 10 shows the block diagram of ANFIS based PID for closed loop control of SEPIC. ANFIS has the ability to automatically tune the parameters for PID controller. For the ANFIS, the Takagi Sugeno model is developed with the use of input output (IO) data set. The IO set has been considered from a conventional tuning of PID controller.

The inputs to the ANFIS controller are the error signal e (t) and the derivative of error signal Δe (t). The output from the ANFIS controller are the parameters for PID controller such as proportional gain Kp, integral gain Ki and derivative gain Kd. Figure 11 shows the ANFIS structure model of the proposed system.

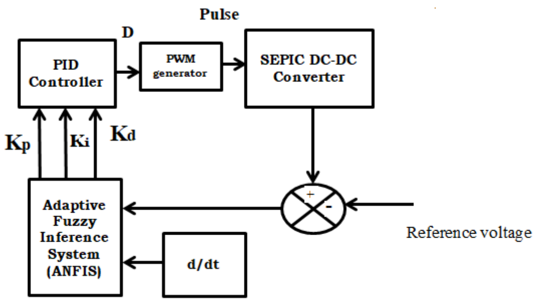

Figure 10. Block diagram of ANFIS-PID controller

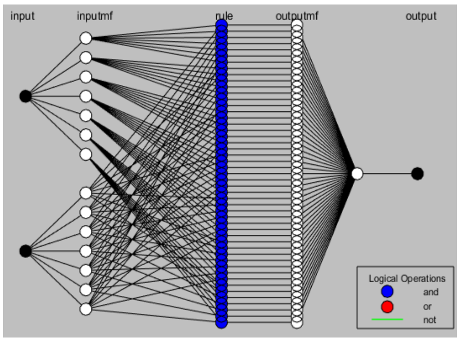

Figure 11. ANFIS structure

The ANFIs adaptation process is done in two steps. First, the consequent parameters training is done by least square method. The premise parameter is fixed at this step. Secondly, by gradient descent principle the approximation error is back propagated through each layer in order to update the parameters. Two fuzzy if then rules from TS model are represented by (21-23):

Rule 1: If (X is A_1) and (Y is B_1) then

$$f_1 = p_1 X + q_1 Y + r_1 \tag{21}$$

Rule 2: If (X is A_2) and (Y is B_2) then

$$f_2 = p_2 X + q_2 Y + r_2 \tag{22}$$

The overall output from ANFIS is

$$\mathbf{O}i^4 = \sum_i W_i * Xf = \frac{\sum_i W_i f}{\sum_i W_i} \tag{23}$$

6. SIMULATION RESULTS

The designed intelligent tuned PID controller with VSWECS and AC-DC-AC converter is implemented using MATLAB/Simulink software tool. The simulations have been performed by maintaining the constant pitch angle. In order to analyze the VSWECS, the step change in wind speed is given as the input to the proposed system. The step changes in wind speed with respect to time shown in Figure 12. With the variation of wind speed, the Figure 13 to Figure 15 show the Diode rectifier output voltage, SEPIC output voltage without controllers. The controlled output voltage from SEPIC is given to the inverter. The output waveform of inverter is shown in Figure 16.

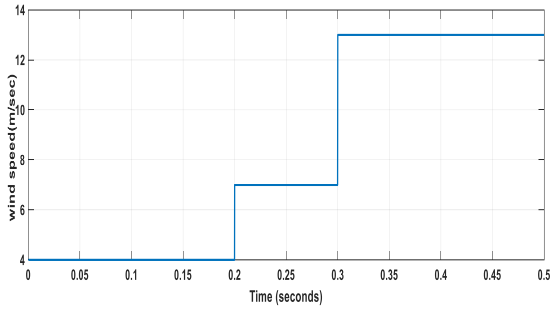

Figure 12. Step change in wind speed

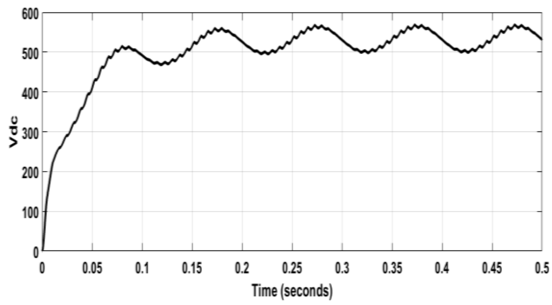

Figure 13. Diode rectifier output voltage for variable wind speed

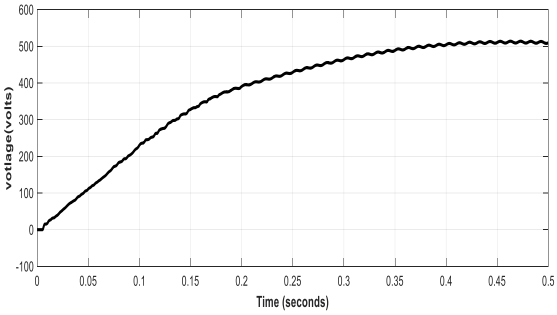

Figure 14. SEPIC output voltage without controller

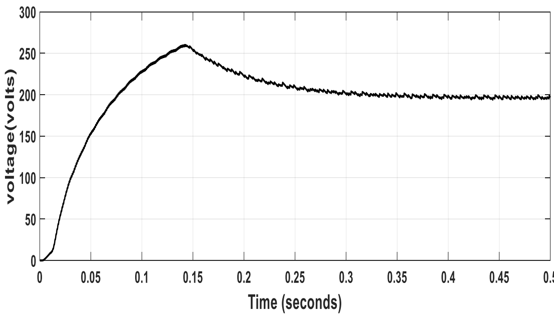

Figure 15. SEPIC output voltage with ANFIS-PID controller

Then the output voltage from inverter is given to the grid or load through the three phase transformer. With the simulation study, variable voltage, and variable frequency obtained from VSWECS was converted as constant voltage (400 Volts) and constant frequency (50Hz) by intelligent tuning of PID controller such as Fuzzy-PID, and ANFIS-PID. The grid voltage and grid current obtained from the proposed model is shown in Figure 17 and Figure 18. The comparison of performance of SEPIC based on intelligent tuned PID controller for VSWECS shown in Table 2.

It is inferred that ANFIS-PID system produces smoother output with less peak overshoot and THD. The steady state error almost zero for all the controllers. The different performance specifications have been improved using the intelligent PID tuning methods but the rise time is less in case of conventional PID tuning. The performance of fuzzy logic controller is comparatively better than that of the conventional PID controller. The best performance in terms of voltage, frequency, THD, settling time and peak overshoot given by ANFIS-PID. This is because of the combined advantages of Neural network and fuzzy used in the ANFIS controller.

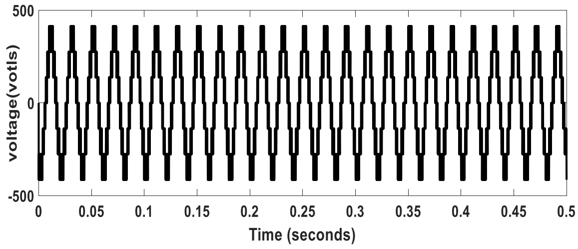

Figure 16. Inverter output voltage

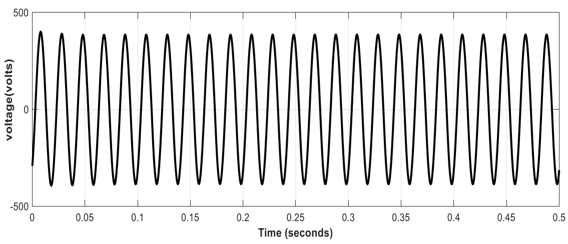

Figure 17. Grid voltage

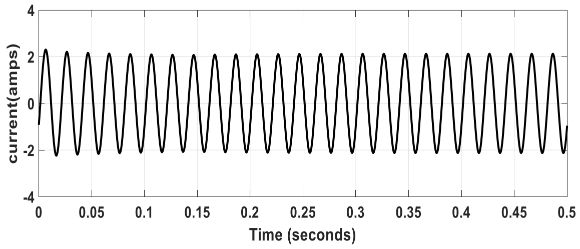

Figure 18. Grid current

Table 2. Comparison among different types of controllers

Parameter	Tuning methods		
	PID	FLC-PID	ANFIS-PID
THD	6.59%	3.43%	0.42%
Rise time(sec)	1.52	1.76	2.78
Settling time(sec)	3.46	5.67	3.52
Steady state error	0	0	0
Peak overshoot (%)	17.3	15.4	1.5
Output voltage(volts)	342	398	400
Frequency(Hz)	47	49	50

7. EXPERIMENTAL RESULTS

The prototype was built to analyze the performance of the proposed AC-DC-AC converter scheme based on intelligent tuning of PID for real time wind energy applications. The experimental setup is shown in Figure 19. The hardware setup consists of power supply, controller setup, and a driver circuit. The MOSFET switch IRF 540 is used in SEPIC and multilevel inverter circuit. The controller of the DC-DC converter is implemented using DSP MSP430F5529. The load is selected as resistive load.

The input to the AC-DC-AC converter is obtained from 230V/12V single-phase transformer. Variable AC voltage of 0-12 volts is selected as the input to the AC-DC-AC converter module. Figure 20 shows the input voltage for the proposed model. The Diode rectifier converts the 0-12 volts AC into unregulated DC voltage shown in Figure 21.

Unregulated DC voltage from Diode rectifier is given as the input to the intelligent controlled SEPIC. The duty cycle of the PWM signal varies according to the change in input DC voltage. The gate pulses generated by the controller are driven through the gate driver circuit. The SEPIC output voltage without controller is shown in Figure 22.

The SEPIC output voltage with conventional proportional Integral and Derivative controller is shown in Figure 23. The controlled output of SEPIC with Fuzzy PID is shown in Figure 24. The controlled output voltage of SEPIC with ANFIS-PID is shown in Figure 25. The output from SEPIC is given to the inverter. The output voltage from cascaded h bridge inverter is shown in Figure 26. The output voltage of the inverter is 6 volts AC.

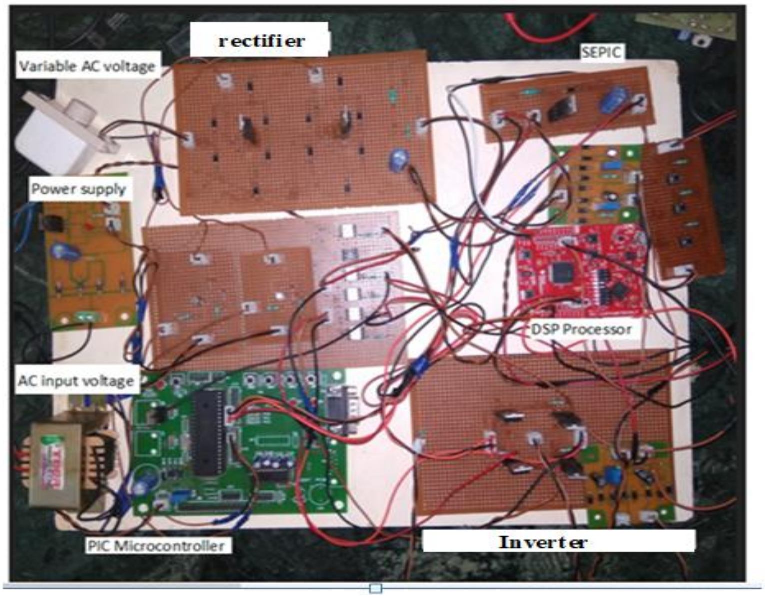

Figure 19. Experimental setup of the proposed method

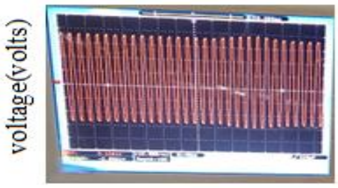

Figure 20. Variable AC input voltage for diode rectifier

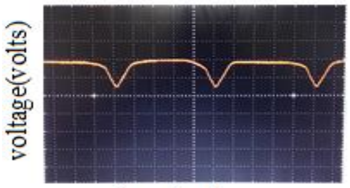

Figure 21. Unregulated DC voltage from diode rectifier

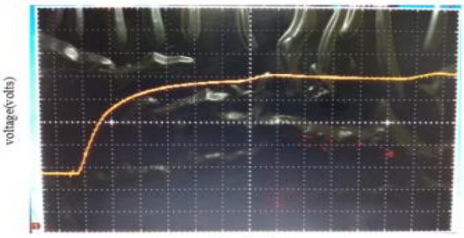

Figure 22. SEPIC output voltage without controller

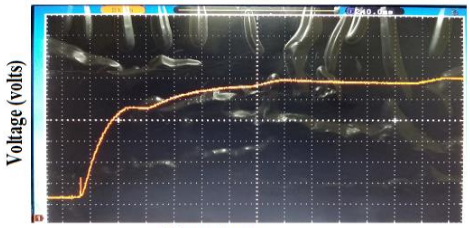

Figure 23. SEPIC output voltage with conventional PID

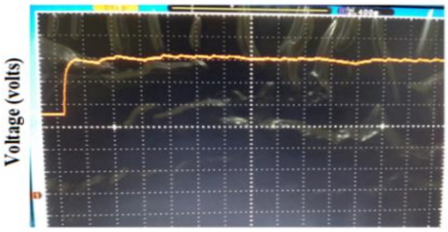

Figure 24. SEPIC output voltage Fuzzy-PID controller

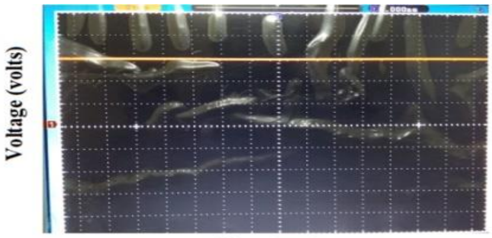

Figure 25. SEPIC output voltage ANFIS-PID controller

Table 3 presents the Total Harmonic Distortion (THD) under variable input voltage and using different intelligent controller. The results of conventional tuning of PID are compared with the intelligent tuning of PID. It is found that the THD is 1.05% for ANFIS-PID controller, which is well below IEEE standard.

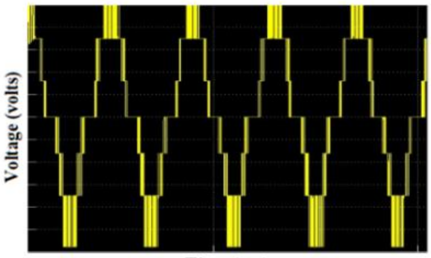

Figure 26. Inverter output voltage

Table 3. Comparison of THD among different tuning methods

Controller	THD
Open loop	55.27%
PID	15.7%
Fuzzy-PID	5.27%
ANFIS-PID	1.05%

8. CONCLUSION

The proposed intelligent tuned PID controller-based Single Ended Primary Inductor Converter (SEPIC) for Maximum Power Point Tracking (MPPT) operation of Wind Energy Conversion System (WECS) is simulated. The mathematical model of mechanical system and electrical system of the VSWECS have been implemented and analyzed. The maximum power point tracking method for WECS have been presented and simulated for different wind speed conditions. The tuning methods of PID have been compared with the intelligent tuning method like fuzzy, and ANFIS. Simulation and experimental results shows that the ANFIS PID provides the improved power quality performance.

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